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MOON for next-generation neutrino-less double-beta decay experiment; present status and perspective

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Abstract. The performance of the MOON detector for a next-generation neutrino-less double-beta decay experiment was evaluated by means of the Monte Carlo method. The MOON detector was found to be a feasible solution for the future experiment to search for the Majorana neutrino mass in the range of 100−30 meV.

1. Introduction

Neutrino-less double-beta decays ($0\nu\beta\beta$) provide a unique probe for lepton-number violating weak processes by ΔL =2, the Majorana nature of the neutrino, the absolute scale and the ordering of the neutrino masses, possible right-handed weak currents, and so on. The effective neutrino masses to be studied by $0\nu\beta\beta$ are around 100 meV and 30 meV in cases of the quasi-degenerate (QD) and the inverted-hierarchy (IH) mass spectra, respectively[1]. To search for $0\nu\beta\beta$ in QD∼IH mass ranges, one has to use $\beta\beta$ isotopes of the order of 0.1∼1 t (tonne) even in cases of such favorable $\beta\beta$ nuclides as ^{82}Se, ^{100}Mo and ^{150}Nd with large phase volumes.

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MOON (Mo/Majorana Observatory Of Neutrinos) has been proposed for a next-generation spectroscopic $0\nu\beta\beta$ experiment[2-6]. This is a brief report on the expected background and the neutrino mass sensitivity of MOON.

2. Outline of MOON Detector

The MOON detector is a stack of multi-layer detector modules, each consists of a scintillator plate for measuring energy and time, two thin detector layers for position and particle identifications, and a thin $\beta\beta$ source film interleaved between them. At present, plastic scintillators and NaI(Tl) scintillators are considered as the candidates for the scintillator plates. For position-sensitive detectors, possible candidates are multi-wire proportional chambers (MWPCs) and Si-strip detectors. All detector components are surrounded by passive shields against external γ-rays and neutrons. Since the $\beta\beta$ source is separated from the detector components, one can measure the decay rate as well as the energy and angular correlations of the two β-rays. This spectroscopic method also enables one to obtain extremely good signal-to-noise ratio by requiring the following conditions for the $0\nu\beta\beta$ event identification;
(a) two adjacent scintillators provide signals with energy losses greater than 500 keV,
(b) no γ-ray or a γ-ray from the excited states of a daughter nucleus is observed in coincidence,
(c) two β-rays are emitted from the same position on a $\beta\beta$ source film, and the tracks of those β-rays are detected by the position-sensitive detector layers on both sides of the source film, and
(d) sum energy of the two β-rays is in the $0\nu\beta\beta$ energy window.

The performance of the MOON detector with plastic scintillators and MWPCs was estimated using the Monte Carlo simulations for various background sources as described below.

3. Backgrounds

The backgrounds due to radioactive isotopes are expected to be dominated by ^{208}Tl and ^{214}Bi from the impurities of Th and U in the $\beta\beta$ source films because of their large Q-values. By assuming realistic contamination levels of 20 μBq/kg and 300 μBq/kg for ^{208}Tl and ^{214}Bi, respectively[9], the background rates in the optimized $0\nu\beta\beta$ window of 2900−3200 keV are estimated as 0.6 counts/t/y (counts per 1 tonne of isotopes for 1 year exposure) and 1.5 counts/t/y, respectively. Fig. 1 shows a calculated sum energy spectra for the β-γ(2.615MeV)-γ(0.583MeV) decay of ^{208}Tl in the source film.

Another main source of the external background is the γ-rays produced by the neutrons due to weak capture reactions of cosmic muons. The energy spectrum of the μ-induced neutrons in an underground laboratory was calculated at a 2000 m water-equivalent location[7]. It is dominated by fast neutrons with the energy up to $\sim$20 MeV. In case of the MOON detector with multi-layer plastic scintillaors, the neutron-induced background is dominated by the inelastic scattering of fast neutrons from ^{12}C in the plastic scintillators, which can be reduced by a factor of $\sim 10^{-4}$ with a 2 m thick water shield. The production rate of the inelastic γ-rays from ^{12}C is about 10^{-6} photons/t/s, and its contribution to the $0\nu\beta\beta$ window amounts to $\sim$0.3 counts/t/y.

As for the intrinsic background due to the high energy tail of the $2\nu\beta\beta$ spectrum in the $0\nu\beta\beta$ window, their counting rates are estimated to be 6.8 counts/t/y, 3.4 counts/t/y, 1.9 counts/t/y for ^{82}Se and 19 counts/t/y, 5.4 counts/ty, 4.6 counts/t/y for ^{100}Mo, depending on the energy resolutions of σ = 2.9%, 2.2%, and 1.7% at 3 MeV. They are much reduced if the energy resolution of the β-ray detectors is improved from the presently achieved value of σ = 2.9%[8].

4. Sensitivity for $0\nu\beta\beta$

The sensitivity for the effective Majorana neutrino mass was evaluated for ^{82}Se and ^{100}Mo by using the backgrounds discussed above. In this estimation a typical thickness of the $\beta\beta$ source film of 30 mg/cm^2 and the energy resolutions of the plastic scintillator of σ = 2.9%, 2.2%, and

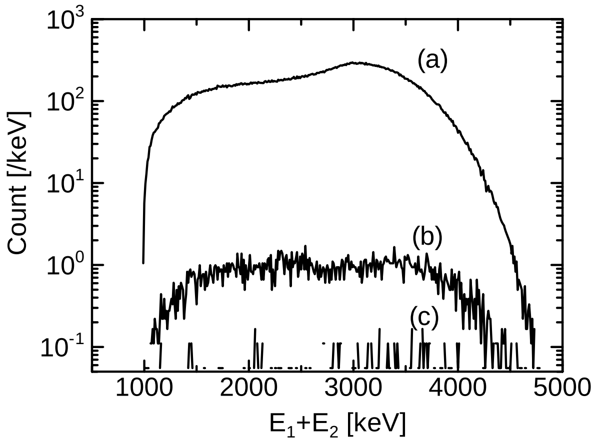

Figure 1. Sum-energy spectra of a pair of adjacent plastic scintillators for β-γ(2.615MeV)-γ(0.583MeV) decay of ^{208}Tl contained in the $\beta\beta$ source film. The curves (a)-(c) are obtained for 10^7 decays with the conditions (a)-(c) described in the text for event selections.

1.7% were employed. Adopting the nuclear matrix elements $M^{0\nu} = 3$ for both ^{82}Se and ^{100}Mo, the mass sensitivities with 90% confidential level for 2 t·y exposure are estimated as 70 meV, 57 meV, and 52 meV for ^{82}Se, and 86 meV, 64 meV, and 56 meV for ^{100}Mo, depending on the energy resolutions of $\sigma = 2.9\%$, 2.2%, and 1.7% at 3 MeV, respectively.

5. Conclusion

MOON is expected to be a realistic solution for exploring $0\nu\beta\beta$ in the effective neutrino mass regions from QD to IH, because of its high sensitivity due to the good resolutions for energies and positions of the β-rays as well as its ability to be expanded from a few ten kilograms to multi tons in the scale of the $\beta\beta$ source quantity.

The background at the $0\nu\beta\beta$ window is expected to be dominated by $2\nu\beta\beta$, and therefore it is crucial for high sensitivity experiment to use β-ray detectors with good energy resolutions. The resolution of $\sigma = 2.9\%$ is fine for the QD mass studies, but $\sigma = 2.2\%$ and 1.7% are required for the IH mass studies. Improvement of the energy resolution is now in progress.

MOON has capabilities to measure various source nuclei, the energy and angular correlations of β- and γ-rays, and the transitions to both the ground and excited states of the daughter nucleus. These unique features of the MOON detector are useful for identifying the light Majorana neutrino process and also for measuring low-energy solar neutrinos in real-time[10].

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